PATENT APPLICATION

LINEAR OPTICAL BEAM TRANSLATOR FOR OPTICAL ROUTING

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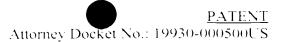120 Betasso Road
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LINEAR OPTICAL BEAM TRANSLATOR FOR OPTICAL ROUTING

BACKGROUND OF THE INVENTION

5   This application relates generally to fiber-optic communications and more specifically to techniques and devices for routing optical signals to different output ports (or, conversely, routing different spectral bands at the output ports to the input port).

10   The Internet and data communications are causing an explosion in the global demand for bandwidth. Fiber optic telecommunications systems are currently deploying a relatively new technology called dense wavelength division multiplexing (DWDM) to expand the capacity of new and existing optical fiber systems to help satisfy this demand. In DWDM, multiple wavelengths of light simultaneously transport
15 information through a single optical fiber. Each wavelength operates as an individual channel carrying a stream of data. The carrying capacity of a fiber is multiplied by the number of DWDM channels used. Today DWDM systems employing up to 80 channels are available from multiple manufacturers, with more channels promised in the future.

20   In all telecommunication networks, there is the need to connect individual channels (or circuits) to individual destination points, such as an end customer or to another network. Systems that perform these functions are called cross-connects. Additionally, there is the need to add or drop particular channels at an intermediate point. Systems that perform these functions are called add-drop multiplexers (ADMs). All of
25 these networking functions are currently performed by electronics — typically an electronic SONET SDH system. However SONET SDH systems are designed to process only a single optical channel. Multi-wavelength systems would require multiple SONET SDH systems operating in parallel to process the many optical channels. This makes it difficult and expensive to scale DWDM networks using SONET SDH
30 technology.

operate at the wavelength level are commonly called "wavelength routing networks" or

"optical transport networks" (OTN). In a wavelength routing network, the individual wavelengths in a DWDM fiber must be manageable. New types of photonic network elements operating at the wavelength level are required to perform the cross-connect, ADM and other network switching functions. Two of the primary functions are optical
5   add-drop multiplexers (OADM) and wavelength-selective cross-connects (WSXC).

In order to perform wavelength routing functions optically today, the light stream must first be de-multiplexed or filtered into its many individual wavelengths, each on an individual optical fiber. Then each individual wavelength must be directed toward
10   its target fiber using a large array of optical switches commonly called an optical cross-connect (OXC). Finally, all of the wavelengths must be re-multiplexed before continuing on through the destination fiber. This compound process is complex, very expensive, decreases system reliability and complicates system management. The OXC in particular is a technical challenge. A typical 40-80 channel DWDM system will require thousands
15   of switches to fully cross-connect all the wavelengths. Opto-mechanical switches, which offer acceptable optical specifications are too big, expensive and unreliable for widespread deployment. New integrated solid-state technologies based on new materials are being researched, but are still far from commercial application.

20   Consequently, the industry is aggressively searching for an all-optical wavelength routing solution that enables cost-effective and reliable implementation of high-wavelength-count systems.

25   SUMMARY OF THE INVENTION

The present invention provides an optical routing apparatus that allows flexible and effective routing of optical signals between input and output ports. The apparatus makes use of one or more linearly actuated mirrors, with different routing
30   configurations of the optical signals resulting from different mirror positions. For each

Thus, in one embodiment of the invention, the optical routing apparatus has an input port configured to provide an optical signal and has a plurality of output ports configured to receive the optical signal. It also has a mirror and a linear actuator disposed to move the mirror to a plurality of positions. The optical signal is directed to a

5   first output port when the mirror is in one of its positions and is directed to a second output port when the mirror is in another of its positions. In different embodiments, the linear actuator moves the mirror perpendicular or parallel to its surface. An advantage where the mirror is moved parallel to its surface is that an optical path that is reflected off the mirror is relatively insensitive to the precise mirror position. In such embodiments,

10   the actuator may lie in the path of the optical signal when the mirror is positioned outside the optical path. In various of such embodiments, the optical path is unobstructed by including a bore through the actuator, or including a nonreflective region transparent to the wavelength of the optical signal in the actuator, or using an actuator constructed of a nonreflective material transparent to that wavelength. In other embodiments, the optical

15   path is also directed with a fixed reflective surface.

In another embodiment of the invention, the optical routing apparatus has two input ports and two output ports. A mirror disposed on a linear actuator allows at least two configurations for directing two optical signals. In the first configuration, the

20   optical signal provided from the first (second) input port is directed to the first (second) output port, and in the second configuration, the optical signal provided from the first (second) input port is directed to the second (first) output port. In one embodiment, a single mirror disposed to move parallel to its surface is used. Where the actuator is positioned in the path of one of the optical signals, it may include a bore or include

25   nonreflective material transparent to the signal's wavelength so that propagation of the signal is unobstructed. In a particular embodiment, the mirror is reflective on both sides, with different optical paths reflecting off the two sides of the mirror. In still other embodiments, fixed reflective surfaces are also used in directing the optical signals.

30   In yet a further embodiment of the invention that permits routing a signal

second configuration, three linearly actuated mirrors are used. All of the mirrors may use the same parallel or perpendicular form of actuation, or a combination of parallel- and

perpendicular-actuated mirrors may be used. Such embodiments may make use of the techniques described above to permit an actuator that moves a mirror parallel to its surface to lie within an optical path without obstructing propagation of the signals. Such embodiments may also include fixed reflective surfaces to direct the optical signals.

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BRIEF DESCRIPTION OF THE DRAWINGS

A further understanding of the nature and advantages of the present invention may be realized by reference to the remaining portions of the specification and 10 the drawings wherein like reference numerals are used throughout the several drawings to refer to similar components.

Fig. 1 illustrates the optical pathways taken in one embodiment using a plunger configuration of a linearly actuated steering mirror for a 1×2 optical switch;

15 Fig. 2 illustrates the optical pathways taken in one embodiment using a slider configuration of a linearly actuated steering mirror for a 1×2 optical switch;

Fig. 3 illustrates the optical pathways taken in one embodiment where a 2×2 optical switch is implemented with a triple-slider configuration of linearly actuated steering mirrors; part (a) shows the relative positions of the mirrors and optical pathways 20 by superposing the two switch positions while parts (b) and (c) show the pathways for the switch positions individually;

Fig. 4 illustrates the optical pathways taken in one embodiment where a 2×2 optical switch is implemented with a single linearly actuated steering mirror in a slider configuration; part (a) shows the relative positions of the mirror and optical 25 pathways by superposing the two switch positions while parts (b) and (c) show the pathways for the switch positions individually; and

Fig. 5 illustrates the optical pathways taken in one embodiment where a 2×2 optical switch is implemented with three linearly actuated steering mirrors, two of which are in a plunger configuration and one of which is in a slider configuration; part (a)

DESCRIPTION OF THE SPECIFIC EMBODIMENTS

I. Introduction

5   The following description sets forth embodiments of a linear optical beam translator for use in an optical wavelength router according to the invention. Embodiments of the invention can be applied to network elements such as optical add-drop multiplexers (OADMs), optical cross-connects (OXCs), and wavelength-selective cross-connects (WSXCs), among others, to achieve the goals of optical networking

10   systems.

The general functionality of one optical wavelength router that can be used with the embodiments of the invention is described in detail in the copending, commonly assigned United States Patent Application, filed November 16, 1999 and assigned Serial

15   No. 09/422,061, entitled "Wavelength Router," which is herein incorporated by reference for all purposes. As described therein, such an optical wavelength router accepts light having a plurality of spectral bands at an input port and selectively directs subsets of the spectral bands to desired ones of a plurality of output ports. As used herein, the terms "input port" and "output port" are intended to have broad meanings. At the broadest, a

20   port is defined by a point where light enters or leaves the optical router. For example, the input (or output) port could be the location of a light source (or detector) or the location of the downstream end of an input fiber (or the upstream end of an output fiber). The routing geometries described below are independent of the wavelength of the optical signal. Accordingly, they are used by themselves in some embodiments, while in other

25   embodiments they are used in combination with a dispersive element (such as described in Appl. No. 09 422,061) for optical signals multiplexed with various wavelength components.

Embodiments of the invention are described below for two types of optical

30   switches referred to herein as the "1×2" and "2×2" switch, and appropriate modifications

port to one of two output ports in the router. The "2×2" switch is used to direct a pair of

signals from two input ports to two output ports: in one configuration ("passthrough") the first and second input signals are directed to the first and second output ports respectively, while in the other configuration ("crossed"), the first and second input signals are directed to the second and first output ports respectively.

For example, in one embodiment the "1×2" switch is used to direct a signal with a first wavelength λ_1 from the input port to a first output port and to direct a signal with a second wavelength λ_2 from the input port to a second output port. The "2×2" switch may be used, for example, to add a signal of wavelength λ_1 and drop a signal of wavelength λ_2 from a trunk line. In such an embodiment, the two input ports correspond to a "trunk in" port and an "add" port; the two output ports correspond to a "trunk out" port and a "drop" port. In the passthrough configuration, the "trunk in" input signal is routed to the "trunk out" output port and the "add" input signal is routed to the "drop" output port. In the crossed configuration, the "trunk in" input signal is routed to the "drop" output port and the "add" input signal is routed to the "trunk out" output port. Other uses of such switch configurations are possible as are alternative switch configurations.

In embodiments of the invention, the optical signals are routed with steering mirrors that are displaced linearly with actuators, sometimes in combination with fixed reflective surfaces. Such linear displacement is preferably in a direction perpendicular ("plunger configuration") or parallel ("slider configuration") to the plane in which the reflective surface of the mirror lies, although more generally the invention encompasses linear translation of a steering mirror in any direction. Various technologies may be used to drive the linear translators. Without limitation, examples of appropriate driving technologies include the use of piezoelectric actuator stacks, electrorestrictive actuator stacks, micro-electromechanical-system ("MEMS") actuator stacks, and MEMS linear translators. Linear translation of mirrors avoids the introduction of tilt into propagating wavefronts and can be implemented with fewer actuators than required for other steering mirrors. In the case of the slider configuration, the amount of translation

and improve the robustness of router assemblies when compared with tilting steering

mirrors. In various embodiments, the routing geometries of the invention are coupled with additional optical elements, such as focusing lenses, gradient index lenses, and/or diffraction gratings); an example of how such additional elements may be used in combination with the routing geometries is illustrated in Appl. No. 09/422,061, although

5   other combinations will be apparent to those of skill in the art upon reading this disclosure.

II. Plunger Configurations: 1×2 Switch

10   In the plunger configuration, a high-reflectivity mirror is affixed to a linear actuator that moves the mirror in a direction perpendicular to the plane of its reflective surface. In one embodiment, the actuator is configured to limit the position of the mirror to one of two locations. Such an embodiment is illustrated in Fig. 1 where the plunger configuration is implemented as part of a 1×2 fiber switch. The 1×2 switch permits an

15   optical signal from the input port 102 to be directed to a first output port 104 or to a second output port 106. The mirror 118 is attached to a plunger actuator 120 that is affixed to surface 116. The actuator 120 is configured to position the mirror 118 in either position "1" or position "2," in each of which the reflective plane of the mirror makes a 45° angle with the optical path 108 from the input port 102. When the mirror 118 is in

20   location "1," the optical signal along path 108 from the input port 102 is reflected off the mirror 118, off of reflective surface 114, and along path 110 to the first output port 104. When the mirror 118 is instead in location "2," the optical signal along path 108 is reflected off mirror 118 and surface 114 along path 112 to the second output port 106. Reflective surface 114 is perpendicular to the reflective plane of the mirror 118, so that

25   the return paths 110 and 112 to the output ports 104 and 106 are parallel to the path 108 from the input port 102.

III. Slider configurations

30   i 1×2 Switch

        shown in Fig. 2. In this embodiment, the slider actuator 122 is configured to move the

mirror 118 in a direction parallel to the plane of the mirror's reflective surface, along axis 124. The actuator 122 may be in a retracted or extended position. Accordingly, when the actuator 122 is retracted to position "1," mirror 118 is not at all in the path of the optical signal from the input port 102. The signal thus propagates along path 108, is reflected off of reflective surfaces 116 and 114, and propagates along path 110 to the first output port 104. This path is changed when the mirror 118 is interposed to intersect the signal propagating along path 108. The axis 124 along which the mirror is moved is set at 45° to the optical path 108. When the actuator 122 is extended to position "2," shown with a dashed line, the signal is reflected off the mirror 118 and the surface 114 along path 112 to the second output port 106.

As for the plunger configuration for the 1×2 switch, reflective surface 114 is perpendicular to the reflective plane of the mirror 118, so that the return paths 110 and 112 to the output ports 104 and 106 are parallel to the path 108 from the input port 102. The positioning of the mirror 118 requires relatively low accuracy when compared either with the accuracy needed for tilting mirrors or with the accuracy required for a translating mirror using the plunger configuration. Provided the mirror 118 intersects path 108, the optical arrangement ensures that the signal will be directed along path 110 or 112 as required to the appropriate output port 106. Even substantial deviations in the position of the mirror along axis 124 are tolerable. As seen below, this advantage generally inheres to any embodiment using the slider configuration.

ii. Triple-Slider 2×2 Switch

A slider configuration can also be used for the 2×2 switch. One such embodiment that uses three linearly actuated translators is shown in Fig. 3. As before, each actuator may be in either an extended or a retracted position. For ease of understanding, the figure is shown in three parts: Fig. 3(a) shows a superposition of the actuator positions, steering mirror positions, and optical pathways for the two switch states, while Fig. 3(b) and Fig. 3(c) respectively break this down into for the two

switch positions, while Figs. 3(b) and Fig. 3(c) are more useful to follow the optical pathways that those positions produce.

Referring generally to Fig. 3 as a whole, the 2×2 switch comprises two input ports 202 and 204 and two output ports 206 and 208. In the passthrough configuration ("1"), an optical signal from input port 202 (204) is directed to output port 206 (208), while in the crossed configuration ("2"), an optical signal from input port 202 (204) is directed to output port 208 (206). The three slider actuators are positioned at right angles such that actuator 210 is perpendicular to actuator 212, which is itself perpendicular to actuator 214. This same relative perpendicularity thus applies to the three steering mirrors respectively affixed to the actuators, so that mirror 220 is perpendicular to mirror 222, which is itself perpendicular to mirror 224. All three mirrors 220, 222, and 224 are oriented such that the plane of their reflective surfaces makes a 45° angle with an optical path followed by a signal either from one of the input ports 202 or 204 or to one of the output ports 206 or 208. Such optical signals are thus always parallel. Reflective surfaces 216 and 219 are provided to direct some of the optical signals as explained below. In the illustrated embodiment, reflective surface 216 is a fixed mirror formed on a fixed block 218, although alternative means for providing reflective surface 216 will be apparent to those of skill in the art and are within the scope of the invention. In the illustrated embodiment, reflective surface 219 is a plane mirror, although alternatives are again within the scope of the invention.

When the switch is in the passthrough configuration ("1"; Fig. 3(b)), actuators 210 and 212 are in a retracted position and actuator 214 is in an extended position. When actuators 210 and 212 are in their retracted positions, mirrors 220 and 222 do not participate in the optical routing. The optical signal from input port 202 follows path 226, being reflected off reflective surface 216 and mirror 224 to output port 206. The optical signal from input port 204 follows path 228, being reflected off reflective surfaces 216 and 219 to propagate through actuator 214 to output port 208. In the illustrated embodiment, actuator 214 comprises a bore 250 configured such that path

wavelength of the optical signal. In still another alternative embodiment, the bore 250 is

replaced with a transparent antireflective material while the remainder of the actuator 214 is formed of a different material.

When the switch is in the crossed configuration ("2"; Fig. 3(c)), actuators 5 210 and 212 are in an extended position and actuator 214 is in a retracted position. The optical signal from input port 202 follows path 230, reflecting off mirrors 220 and 224 to output port 208. The optical signal from input port 204 follows path 232, being reflected off reflective surface 216 and mirror 222 to output port 206. In this configuration, all three mirrors are used.

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iii. Single-Slider 2×2 Switch

In an alternative embodiment, a single linearly actuated slider that can be in an extended or retracted position is used as part of a 2×2 switch. As shown in Fig. 4, a 15 steering mirror 268 that is reflective on both sides is moved by the actuator 260 along a direction at 45° to the paths followed by the optical signals. Fig. 4 is presented in three parts: Fig. 4(a) shows the two switch positions ("1" and "2") simultaneously, permitting easy comparison of the optical paths used for the two positions; Figs. 4(b) and 4(c) respectively show the configurations for the first and second positions individually to 20 highlight the individual optical paths used. In the illustrated embodiment, the actuator 260 includes a bore 262 to permit the propagation of an optical signal through the actuator when it would otherwise block the optical path. In alternative embodiments, nonreflective materials transparent at the wavelengths of the optical signals replace either the bore 262 or the entire actuator 260, thereby also permitting propagation through the 25 actuator 260 as necessary.

Referring generally to Fig. 4 as a whole, the switch comprises, in addition to the actuator 260, two reflective surfaces 264 and 266 that join at a 90° angle, the first surface 264 being parallel to the steering mirror 268 and the second surface 266 being
_____ mirror 268. The passthrough configuration ("2"; Fig. 4(c)),

optical signal from input port 202 follows path 274 through the bore 262 of the actuator

260, is reflected off the first reflective surface 264 to the steering mirror 268, where it is reflected back to the first reflective surface 264, from which it is reflected to the second reflective surface 266, from which it is reflected to output port 206. The optical signal from input port 204 follows path 276, being reflected off the steering mirror 268 and the

5   second reflective surface 266 to output port 208.

In the crossed configuration ("1'" Fig. 4(b)), wherein a signal is propagated from input port 202 (204) to output port 208 (206), the actuator 260 is in the retracted position so that the steering mirror 268 is not involved in the routing. The path followed

10   by the two signals is very similar in such a configuration: the signal from input port 202 (204) follows path 270 (272), being reflected off reflective surface 264 and reflective surface 266 to output port 208 (206).

IV. Mixed Plunger-Slider Configurations: 2×2 Switch

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Embodiments of the invention also include configurations that use a combination of plunger actuators and slider actuators. One such embodiment is illustrated in Fig. 5 using two steering mirrors 288 and 290 attached respectively to linear translators 282 and 284 in the plunger configuration and one steering mirror 292 attached to a linear translator 286 in the slider configuration. Each of the linear translators 282,

20   284, and 292 can be in a retracted or extended position, the dotted lines in Fig. 5(a) being used to show the extended configuration of each translator. Each linear translator moves its respective mirror along a direction inclined 45° to the input and output optical paths so that each of the steering mirrors is also inclined 45° to those paths. In this embodiment,

25   surface 294 is also used in directing the optical signals and is therefore reflective. It is oriented parallel to mirror 292 so that it too is inclined 45 to the input and output optical paths. As before, part (a) of the figure shows a superposition of the two switch positions to facilitate comparison of the relative locations of the actuators and pathways, while parts (b) and (c) show the optical pathways for each switch position individually.

port 206 (208), the first plunger actuator 282 is in a retracted position, the second plunger

actuator 284 is in an extended position, and the slider actuator 286 is in an extended position. The optical signal from input port 202 thus propagates along path 300 to mirror 288 where it is reflected to mirror 292, which in turn reflects it back along path 304 to output port 206. The optical signal from port 204 propagates along path 302 to mirror

5   290 where it is reflected to reflective surface 294, which in turn reflects it back along path 306 through the slider actuator 286 to output port 208. In the illustrated embodiment, propagation of the optical signal through the slider actuator 286 is achieved with a bore 296 through the actuator 286; in alternative embodiments, the bore 296 or the entire actuator 286 is substituted with a nonreflective material that is transparent to the

10   wavelength of the optical signal.

In the crossed configuration ("1"; Fig. 5(b)), where an optical signal is propagated from input port 202 (204) to output port 208 (206), the first plunger actuator 282 is in an extended position, the second plunger actuator 284 is in a retracted position,

15   and the slider actuator 286 is in a retracted position. In this configuration, the optical signals are routed by the same elements as in the passthrough configuration. The optical signal from input port 202 propagates along path 300, reflects off mirror 288 to mirror 292, where it is reflected along path 306 to output port 208. The optical signal from port 204 propagates along path 302 to mirror 290 where it is reflected to reflective surface

20   294, which in turn reflects it along path 304 to output port 206. While the signal from input port 202 is always routed by mirrors 288 and 292 and the signal from input port 204 always routed by mirror 290 and reflective surface 294, the final path is different because of the different positions of the mirrors. In this embodiment, all three steering mirrors are used when the 2×2 switch is in either the passthrough or crossed configuration.

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Having described several embodiments, it will be recognized by those of skill in the art that various modifications, alternative constructions, and equivalents may be used without departing from the spirit of the invention. Accordingly, the above description should not be taken as limiting the scope of the invention, which is defined in

30   the following claims.

PATENT APPLICATION

WAVELENGTH ROUTER

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WAVELENGTH ROUTER

APPENDIX

The following appendix is filed herewith as a part of the application and is incorporated by reference in its entirety for all purposes:

5   Presentation, titled "Wavelength Router, also referred to as Wavelength Routing Element™ or WRE," containing 28 pages (slides) on 7 sheets.

BACKGROUND OF THE INVENTION

This application relates generally to fiber-optic communications and more

10   specifically to techniques and devices for routing different spectral bands of an optical beam to different output ports. (or conversely, routing different spectral bands at the output ports to the input port).

The Internet and data communications are causing an explosion in the global demand for bandwidth. Fiber optic telecommunications systems are currently

15   deploying a relatively new technology called dense wavelength division multiplexing (DWDM) to expand the capacity of new and existing optical fiber systems to help satisfy this demand. In DWDM, multiple wavelengths of light simultaneously transport information through a single optical fiber. Each wavelength operates as an individual channel carrying a stream of data. The carrying capacity of a fiber is multiplied by the

20   number of DWDM channels used. Today DWDM systems employing up to 80 channels are available from multiple manufacturers, with more promised in the future.

In all telecommunication networks, there is the need to connect individual channels (or circuits) to individual destination points, such as an end customer or to another network. Systems that perform these functions are called cross-connects.

25   Additionally, there is the need to add or drop particular channels at an intermediate point. Systems that perform these functions are called add-drop multiplexers (ADMs). All of these networking functions are currently performed by electronics – typically an electronic SONET/SDH system. However SONET/SDH systems are designed to process only a single optical channel. Multi-wavelength systems would require multiple

technology

The alternative is an all-optical network. Optical networks designed to operate at the wavelength level are commonly called "wavelength routing networks" or "optical transport networks" (OTN). In a wavelength routing network, the individual wavelengths in a DWDM fiber must be manageable. New types of photonic network elements operating at the wavelength level are required to perform the cross-connect, ADM and other network switching functions. Two of the primary functions are optical add-drop multiplexers (OADM) and wavelength-selective cross-connects (WSXC).

In order to perform wavelength routing functions optically today, the light stream must first be de-multiplexed or filtered into its many individual wavelengths, each on an individual optical fiber. Then each individual wavelength must be directed toward its target fiber using a large array of optical switches commonly called as optical cross-connect (OXC). Finally, all of the wavelengths must be re-multiplexed before continuing on through the destination fiber. This compound process is complex, very expensive, decreases system reliability and complicates system management. The OXC in particular is a technical challenge. A typical 40-80 channel DWDM system will require thousands of switches to fully cross-connect all the wavelengths. Opto-mechanical switches, which offer acceptable optical specifications are too big, expensive and unreliable for widespread deployment. New integrated solid-state technologies based on new materials are being researched, but are still far from commercial application.

Consequently, the industry is aggressively searching for an all-optical wavelength routing solution which enables cost-effective and reliable implementation of high-wavelength-count systems.

SUMMARY OF THE INVENTION

The present invention provides a wavelength router that allows flexible and effective routing of spectral bands between an input port and a set of output ports (reversibly, also between the output ports and the input port).

An embodiment of the invention includes a free-space optical train disposed between the input ports and said output ports, and a routing mechanism. The free-space optical train can include air-spaced elements or can be of generally monolithic

                                  more routing elements and cooperates with the other elements in the optical train to

provide optical paths that couple desired subsets of the spectral bands to desired output ports. The routing elements are disposed to intercept the different spectral bands after they have been spatially separated by their first encounter with the dispersive element.

The invention includes dynamic (switching) embodiments and static embodiments. In dynamic embodiments, the routing mechanism includes one or more routing elements whose state can be dynamically changed in the field to effect switching. In static embodiments, the routing elements are configured at the time of manufacture or under circumstances where the configuration is intended to remain unchanged during prolonged periods of normal operation.

In the most general case, any subset of the spectral bands, including the null set (none of the spectral bands) and the whole set of spectral bands, can be directed to any of the output ports. However, there is no requirement that the invention be able to provide every possible routing. Further, in general, there is no constraint on whether the number of spectral bands is greater or less than the number of output ports.

In some embodiments of the invention, the routing mechanism includes one or more retroreflectors, each disposed to intercept a respective one of the spectral bands after the first encounter with the dispersive element, and direct the light in the opposite direction with a controllable transverse offset. In other embodiments, the routing mechanism includes one or more tiltable mirrors, each of which can redirect one of the spectral bands with a controllable angular offset. There are a number of ways to implement the retroreflectors, including as movable rooftop prisms or as subassemblies including fixed and rotating mirrors.

In some embodiments, the beam is collimated before encountering the dispersive element, so as to result in each spectral band leaving the dispersive element as a collimated beam traveling at an angle that varies with the wavelength. The dispersed beams are then refocused onto respective routing elements and directed back so as to encounter the same elements in the optical train and the dispersive element before exiting the output ports as determined by the disposition of the respective routing elements. Some embodiments of the invention use cylindrical lenses while others use spherical lenses. In some embodiments, optical power and dispersion are combined in a single

routed channel has a spectral transfer function that is characterized by a band shape having a relatively flat top. This is achieved by configuring the dispersive element to

have a resolution that is finer than the spectral acceptance range of the individual routing elements. In many cases of interest, the routing elements are sized and spaced to intercept bands that are spaced at regular intervals. The bands are narrower than the band intervals, and the dispersive element has a resolution that is significantly finer than the band intervals.

A further understanding of the nature and advantages of the present invention may be realized by reference to the remaining portions of the specification and the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Figs. 1A, 1B, and 1C are schematic top, side, and end views, respectively, of a wavelength router according to an embodiment of the invention that uses spherical focusing elements;

Figs. 2A and 2B are schematic top and side views, respectively, of a wavelength router according to another embodiment of the invention that uses spherical focusing elements;

Fig. 3 is a schematic top view of a wavelength router according to another embodiment of the invention that uses spherical focusing elements;

Figs. 4A and 4B show alternative implementations of a retroreflector, based on a movable rooftop prism, suitable for use with embodiments of the present invention;

Figs. 4C and 4D are side and top views of a rooftop prism array fabricated as a single unit;

Fig. 5A shows an implementation of a retroreflector, based on a movable mirror, suitable for use with embodiments of the present invention;

Figs. 5B and 5C are side and top views of an implementation of a retroreflector array, based on micromirrors, suitable for use with embodiments of the present invention;

Fig. 5D is a side view of an alternative implementation of a retroreflector array based on micromirrors;

focusing elements;

Figs. 7A and 7B are schematic top and side views, respectively, of a wavelength router according to another embodiment of the invention that uses cylindrical focusing elements;

Figs. 8A and 8B are schematic top and side end views, respectively, of a wavelength router according to an embodiment of the invention that combines spherical focusing power and dispersion in a single element;

Figs. 9A and 9B are schematic top and side views, respectively, of a wavelength router according to an embodiment of the invention that combines cylindrical focusing power and dispersion in a single element;

Figs. 10A shows a preferred band shape;

Figs. 10B and 10C show the differential path length for a representative path from Fig. 1A; and

Figs. 11A and 11B are schematic top and side views, respectively, of a wavelength router according to an embodiment of the invention that uses a prism as the dispersive element.

DESCRIPTION OF SPECIFIC EMBODIMENTS

Introduction

The following description sets forth embodiments of an all-optical wavelength router according to the invention. Embodiments of the invention can be applied to network elements such as optical add-drop multiplexers (OADMs) and wavelength-selective cross-connects (WSXCs) to achieve the goals of optical networking systems.

The general functionality of the wavelength router is to accept light having a plurality of (say N) spectral bands at an input port, and selectively direct subsets of the spectral bands to desired ones of a plurality of (say M) output ports. Most of the discussion will be with reference to dynamic (switching) embodiments where the routing mechanism includes one or more routing elements whose state can be dynamically changed in the field to effect switching. The invention also includes static embodiments which the routing elements are configured at the time of manufacture or under

The embodiments of the invention include a dispersive element, such as a diffraction grating or a prism, which operates to deflect incoming light by a wavelength-dependent amount. Different portions of the deflected light are intercepted by different routing elements. Although the incoming light could have a continuous spectrum,

5 adjacent segments of which could be considered different spectral bands, it is generally contemplated that the spectrum of the incoming light will have a plurality of spaced bands.

The terms "input port" and "output port" are intended to have broad meanings. At the broadest, a port is defined by a point where light enters or leaves the

10 system. For example, the input (or output) port could be the location of a light source (or detector) or the location of the downstream end of an input fiber (or the upstream end of an output fiber). In specific embodiments, the structure at the port location could include a fiber connector to receive the fiber, or could include the end of a fiber pigtail, the other end of which is connected to outside components. Most of the embodiments contemplate

15 that light will diverge as it enters the wavelength router after passing through the input port, and will be converging within the wavelength router as it approaches the output port. However, this is not necessary.

The International Telecommunications Union (ITU) has defined a standard wavelength grid having a frequency band centered at 193,100 GHz, and another band at

20 every 100 GHz interval around 193,100 GHz. This corresponds to a wavelength spacing of approximately 0.8 nm around a center wavelength of approximately 1550 nm, it being understood that the grid is uniform in frequency and only approximately uniform in wavelength. Embodiments of the invention are preferably designed for the ITU grid, but finer frequency intervals of 25 GHz and 50 GHz (corresponding to wavelength spacings

25 of approximately 0.2 nm and 0.4 nm) are also of interest.

The ITU has also defined standard data modulation rates. OC-48 corresponds to approximately 2.5 GHz (actually 2.488 GHz), OC-192 to approximately 10 GHz, and OC-768 to approximately 40 GHz. The unmodulated laser bandwidths are on the order of 10-15 GHz. In current practice, data rates are sufficiently low (say

30 OC-192 on 100 GHz channel spacing) that the bandwidth of the modulated signal is

OC-768 on 100 GHz channel spacing), problems relating to the band shape of the channel is not great. Techniques for addressing these problems will be described below.

Embodiments with Spherical Focusing Elements

Figs. 1A, 1B, and 1C are schematic top, side, and end views, respectively, of a wavelength router 10 according to an embodiment of the invention. The general functionality of wavelength router 10 is to accept light having a plurality of (say N)

5   spectral bands at an input port 12, and selectively direct subsets of the spectral bands to desired ones of a plurality of (say M) output ports, designated 15(1 … M). The output ports are shown in the end view of Fig. 1C as disposed along a line 17 that extends generally perpendicular to the top view of Fig. 1A. The input and output ports are shown as communicating with respective input and output optical fibers, but it should be

10   understood that the input port could also receive light directly from a light source, and the output ports could be coupled directly to optical detectors. The drawing is not to scale.

Light entering wavelength router 10 from input port 12 forms a diverging beam 18, which includes the different spectral bands. Beam 18 encounters a lens 20 which collimates the light and directs it to a reflective diffraction grating 25. Grating 25

15   disperses the light so that collimated beams at different wavelengths are directed at different angles back towards lens 20. Two such beams are shown explicitly and denoted 26 and 26' (the latter drawn in dashed lines). Since these collimated beams encounter the lens at different angles, they are focused at different points along a line 27 in a transverse focal plane. Line 27 extends in the plane of the top view of Fig. 1A.

20   The focused beams encounter respective ones of plurality of retroreflectors, designated 30(1 … N), located near the focal plane. The beams are directed, as diverging beams, back to lens 20. As will be described in detail below, each retroreflector sends its intercepted beam along a reverse path that may be displaced in a direction perpendicular to line 27. More specifically, the beams are displaced along

25   respective lines 35(1 … N) that extend generally parallel to line 17 in the plane of the side view of Fig. 1B and the end view of Fig. 1C.

In the particular embodiment shown, the displacement of each beam is effected by moving the position of the retroreflector along its respective line 35(i). In other embodiments, to be described below, the beam displacement is effected by a

30   reconfiguration of the retroreflector. It is noted that the retroreflectors are shown above

The beams returning from the retroreflectors to the collimating lens 20 are directed once more to grating 25. Grating 25, on the second encounter, removes the

angular separation between the different beams, and directs the collimated beams back to lens 20, which focuses the beams. However, due to the possible displacement of each beam by its respective retroreflector, the beams will be focused at possibly different points along line 17. Thus, depending on the positions of the retroreflectors, each beam is

5   directed to one or another of output ports 15(1 ... M).

In sum, each spectral band is collimated, encounters the grating and leaves the grating at a wavelength-dependent angle, is focused on its respective retroreflector such that is displaced by a desired amount determined by the retroreflector, is collimated again, encounters the grating again so that the grating undoes the previous dispersion, and

10   is focused on the output port that corresponds to the displacement imposed by the retroreflector. In the embodiment described above, the light traverses the region between the ports and the grating four times, twice in each direction.

This embodiment is an airspace implementation of a more generic class of what are referred to as free-space embodiments. In some of the other free space

15   embodiments, to be described below, the various beams are all within a body of glass. The term "free-space" refers to the fact that the light within the body is not confined in the dimensions transverse to propagation, but rather can be regarded as diffracting in these transverse dimensions. Since the second encounter with the dispersive element effectively undoes the dispersion induced by the first encounter, each spectral band exits

20   the router with substantially no dispersion.

Figs. 2A and 2B are schematic top and side views, respectively, of a wavelength router, designated 10', according to an embodiment of the invention. The same reference numerals or primed or suffixed reference numerals will be used for elements corresponding to those in Figs. 1A-1C. This embodiment differs from the

25   embodiment of Figs. 1A-1C in that it uses a transmissive diffraction grating 25' and a pair of lenses 20a and 20b. Thus, this embodiment can be considered an unfolded version of the embodiment of Figs. 1A-1C.

Light entering wavelength router 10' from input port 12 forms diverging beam 18, which includes the different spectral bands. Beam 18 encounters first lens 20a,

30   which collimates the light and directs it to grating 25'. Grating 25' disperses the light so

beams. The focused beams encounter respective ones of a plurality of retroreflectors ... Ni, located near the focal plane. The beams are reflected, and emerge as diverging

beams, back to lens 20b, are collimated and directed to grating 25'. Grating 25', on the second encounter, removes the angular separation between the different beams, which are then focused in the plane of output ports 15(1 ... M).

In the specific implementation, input port 12, lens 20a, grating 25', lens 20b, and the retroreflectors are spaced at approximately equal intervals, with the two lenses having equal focal lengths and the distance between the input port and the retroreflectors being four times (4x) the focal length. Thus the focal lengths and the relative positions define what is referred to as a "4f relay" between input port 12 and the retroreflectors, and also a 4f relay between the retroreflectors and the output ports. This configuration is not necessary, but is preferred. The optical system is preferably telecentric.

Fig. 3 is a schematic top view of a wavelength router 10" according to an embodiment of the invention. This embodiment is a solid glass embodiment that uses a concave reflector 40 in the place of lens 20 of the first embodiment (or lenses 20a and 20b in the second embodiment). Thus, this embodiment can be considered a further folded version of the embodiment of Figs. 1A-1C. As above, light entering wavelength router 10" from input port 12 forms diverging beam 18, which includes the different spectral bands. Beam 18 encounters concave reflector 40, which collimates the light and directs it to reflective diffraction grating 25. Grating 25 disperses the light so that collimated beams at different wavelengths are directed at different angles back toward reflector 40. Two such beams are shown explicitly, one in solid lines and one in dashed lines. Since these collimated beams encounter the reflector at different angles, they are focused at different points in a transverse focal plane.

The focused beams encounter retroreflectors 30(1 ... N) located near the focal plane. The operation in the reverse direction is as described in connection with the embodiments above, and the beams follow the reverse path, which is displaced in a direction perpendicular to the plane of Fig. 3. Therefore, the return paths directly underlie the forward paths and are therefore not visible in Fig. 3. On this return path, the beams encounter concave reflector 40, reflective grating 25', and concave reflector 40, the final encounter with which focuses the beams to the desired output ports (not shown in

Rooftop-Prism-Based Retroreflector Implementations

Figs. 4A and 4B show alternative implementations of a retroreflector, based on a movable rooftop prism, suitable for use with embodiments of the present invention. The retroreflectors, designated 30a and 30b could be used to implement array

5   30(1 ... N) in the embodiments described above.

Fig. 4A shows schematically the operation of a retroreflector, designated 30a, that operates to displace an incoming beam by different amounts depending on displacement of the retroreflector transversely relative to the beam. The left portion of the figure shows the retroreflector in a first position. A second, downwardly displaced,

10   position is shown in phantom. The right portion of the figure shows the retroreflector displaced to the second position, whereupon the reflected beam is displaced downwardly by an amount proportional to the retroreflector displacement. The retroreflector is shown as a rooftop prism, and the operation is based on total internal reflection. It is also possible to implement the retroreflector as a pair of mirrors in a V-shaped configuration.

15   A retroreflector of this type has the property that while the reflected beam is offset from the incident beam by an amount that depends on the incident beam's offset relative to the prism's peak, the total path length is independent of the offset.

Fig. 4B shows schematically the operation of a retroreflector, designated 30b, that includes a rooftop prism element 50 and a pair of matched-index upper and

20   lower plates 51 and 52 in a V-shaped configuration spaced slightly from the prism element. Displacement of the incoming beam is effected by selectively contacting prism element 50 with one or the other of plates 51 or 52. The left portion of the figure shows the prism element contacting upper plate 51, whereupon the input beam passes into the upper plate and is internally reflected by the upper plate and the lower surface of the

25   prism element. The right portion of the figure shows the prism element contacting lower plate 52, whereupon the input beam is internally reflected by the upper surface of the prism element, passes into the lower plate, and undergoes internal reflection at the lower surface of the lower plate. This retroreflector can be seen to provide a beam displacement that can be large relative to the prism element displacement.

30   Figs. 4C and 4D are side and top views of a rooftop prism array fabricated

prism and support plate assembly to define an array of individual prism elements 54 on

respective support tines 55. Two stops 57a and 57b are placed, one above and one below this rooftop prism array. These stops are also polished optically flat. Respective actuators 58 move each prism element against either the top or bottom stop. Any of the prisms held against a given stop are aligned to each other with very high tolerance due to

5   the optical precision in polishing the elongated prism element flat before cutting the slots.

        Associated with each retroreflector is an actuator. This is not shown explicitly in Figs. 4A or 4B, but Fig. 4C shows actuator 58 explicitly. The particular type of actuator is not part of the invention, and many types of actuator mechanisms will be apparent to those skilled in the art. While Fig. 4C shows the actuator explicitly as a

10   separate element (e.g., a piezoelectric transducer), the support plate can be made of a bimorph bender material and thus also function as the actuator. A piezoceramic bender, which is available from Piezo Systems, Inc., 186 Massachusetts Avenue, Cambridge, Massachusetts 02139, is a sandwich structure that bends when subjected to a voltage between electrodes on the two outer surfaces.

15   <u>Movable-Mirror-Based Retroreflector Implementations</u>

        Fig. 5A shows schematically the operation of a retroreflector, designated 30c, that includes a pair of fixed mirrors 60a and 60b inclined with respect to one another (V-shaped, or open configuration as shown) and a rotatable mirror 61. The left portion of the figure shows the rotatable mirror positioned to direct the incoming beam to mirror

20   60a, while the right portion shows the rotatable mirror positioned to direct the incoming beam to mirror 60b. In each of the two orientations, the fixed mirror and the rotatable mirror define an included angle of 90° so as to provide a retroreflecting operation.

        Fig. 5B shows schematically the operation of a retroreflector, designated 30d, that uses micromirrors. Fig. 5C is a top view. A pair of micromirror arrays 62 and

25   63 are mounted to the sloped faces of a V-block 64. A single micromirror 65 in micromirror array 62 and a row of micromirrors 66(1...M) in micromirror array 63 define a single retroreflector. Micrometer arrays may conveniently be referred to as the input and output micromirror arrays, with the understanding the light paths are reversible. The left portion of the figure shows micromirror 65 in a first orientation so as to direct the

incident beam to a second mirror 66(1), which is oriented 90° with respect to micromirror

to direct the incident beam to micromirror 66(M). Thus, micromirror 65 is moved to

select the output position of the beam, while micromirrors 66(1...M) are fixed during normal operation. Micromirror 65 and the row of micromirrors 66 (1...M) can be replicated and displaced in a direction perpendicular to the plane of the figure. While micromirror array 62 need only be one-dimensional, it may be convenient to provide

5   additional micromirrors to provide additional flexibility.

It is preferred that the micromirror arrays are planar and that the V-groove have a dihedral angle of approximately 90° so that the two micromirror arrays face each other at 90°. This angle may be varied for a variety of purposes by a considerable amount, but an angle of 90° facilitates routing the incident beam with relatively small

10   angular displacements of the micromirrors. For example, commercially available micromirror arrays (e.g., Texas Instruments) are capable of deflecting on the order of ±10°. The micromirror arrays may be made by known techniques within the field of micro-electro-mechanical systems (MEMS). In this implementation, the mirrors are formed as structures micromachined on the surface of a silicon chip. These mirrors are

15   attached to pivot structures also micromachined on the surface of the chip. In some implementations, the micromirrors are selectably tilted about an suitably oriented axis using electrostatic attraction.

Fig. 5D shows schematically the operation of a retroreflector, designated 30e, that differs from the implementation shown in Fig. 5C in the use of a prism 69 rather

20   than V-block 64. Corresponding reference numerals are used for like elements. As in the case of the V-groove, it is desired that the micromirror arrays, designated 62' and 63', face each other with an included angle of 90°. To this end, the prism preferably has faces with included angles of 90°, 45°, and 45°, and the micromirror arrays are mounted with the micromirrors facing the prism surfaces that define the right angle.

25   The micromirror arrays are preferably hermetically sealed from the external environment. This hermetic sealing may be accomplished by enclosing each micromirror array in a sealed cavity formed between the surface of the micromirror array on its silicon chip and the surface of the prism. These silicon chips incorporating the micromirror arrays may be bonded around their periphery to the surface of the prism.

30   with an adequate spacing between the mirrors and the surface of the prism. This sealed

by some other suitable peripheral sealing spacer is tuled to both the periphery of the

silicon chip and to the surface of the prism. If desired, each micromirror can be in its own cavity in the chip. The surfaces of the prism preferably have an anti-reflection coating.

The retroreflector implementations that comprise two arrays of tiltable micromirrors are currently preferred. Each micromirror in the input micromirror array receives light after the light's first encounter with the dispersive element, and directs the light to a mirror in the output micromirror array. By changing the angle of the mirror in the input array, the retroreflected light has a transverse displacement that causes it to encounter the dispersive element and exit the selected output port. As mentioned above, embodiments of the invention are reversible. The implementation with the V-block is generally preferred for embodiments where most of the optical path is in air, while the implementation with the prism is generally preferred for embodiments where most of the optical path is in glass. As an alternative to providing a separate prism or V-block, the input array mounting face and the output array mounting face may be formed as integral features of the router's optical housing.

The input micromirror array preferably has at least as many rows of micromirrors as there are input ports (if there are more than one), and as many columns of mirrors as there are wavelengths that are to be selectably directed toward the output micromirror array. Similarly, The output micromirror array preferably has at least as many rows of micromirrors as there are output ports, and as many columns of mirrors as there are wavelengths that are to be selectably directed to the output ports.

In a system with a magnification factor of one-to-one, the rows of micromirrors in the input array are parallel to each other and the component of the spacing from each other along an axis transverse to the incident beam corresponds to the spacing of the input ports. Similarly, the rows of micromirrors in the output array are parallel to each other and spaced from each other (transversely) by a spacing corresponding to that between the output ports. In a system with a different magnification, the spacing between the rows of mirrors would be adjusted accordingly.

Embodiments with Cylindrical Focusing Elements

Figs. 6A and 6B are schematic top and side views, respectively, of a

the embodiment of Figs. 2A and 2B, but differs from that embodiment in that wavelength

router 70 uses cylindrical lenses rather than spherical lenses, and tiltable mirrors rather than retroreflectors. The general functionality of wavelength router 70 is the same as the other embodiment, namely to accept light having a plurality of spectral bands at input port 12, and selectively direct subsets of the spectral bands to desired ones of a plurality

5   of output ports 15(1 ... M).

The cylindrical lenses include a pair of lenses 72a and 72b, each having refractive power only in the plane of the top view (Fig. 6A), and a pair of lenses 75a and 75b each having refractive power only in the plane of the side view (Fig. 6B). As such, lenses 72a and 72b are drawn as rectangles in the plane of Fig. 6B, and lenses 75a and

10   75b are drawn as rectangles in the plane of Fig. 6A.

Light entering wavelength router 70 from input port 12 forms diverging beam 18, which includes the different spectral bands. Beam 18 encounters lens 72a, which collimates the light in one transverse dimension, but not the other, so that the beam has a transverse cross section that changes from circular to elliptical (i.e., the beam

15   continues to expand in the plane of Fig. 6B, but not in the plane of Fig. 6A. The beam encounters lens 75a, grating 25', and lens 75b. Lenses 75a and 75b, together, collimate the light that is diverging in the plane of Fig. 6B so that the beam propagates with a constant elliptical cross section. Grating 25' disperses the light in the plane of Fig. 6A so that beams at different wavelengths are transmitted at different angles in the plane of Fig.

20   6A, but not in the plane of Fig. 6B.

The collimated beams encounter lens 72b, and are focused to respective lines. The focused beams encounter respective ones of plurality of tiltable mirrors 80(1 ... N), located near the focal plane. The beams are directed, diverging only in the plane of Fig. 6A, to lens 72b. Depending on the tilt angles of the respective mirrors, the beams

25   are angularly displaced in the plane of Fig. 6B. The return beams undergo different transformations in the planes of Figs. 6A and 6B, as will now be described.

In the plane of Fig. 6A, the beams are collimated by lens 72b, and directed once more to grating 25' (in this plane, lenses 75b and 75a do not change the collimated character of the beams). Grating 25', on this second encounter, removes the angular

30   separation between the different beams, and directs the collimated beams back to lens

plane that coincide with the projection of the input beam.

In the plane of Fig. 6B, the beams are focused by lenses 75a and 75b onto the output ports. However, due to the possible angular displacement of each beam by its respective mirror, the beams will be directed to one or another of output ports 15(1 ... M). In Fig. 5B, grating 25' and lenses 72b and 72a do not affect the direction of the beams, or

5   whether the beams are diverging, collimated, or converging The lenses 75a and 75b provide a Fourier relation in the plane of the side view, between mirrors 80(1 ... N) and output ports 15(1 ...M). This Fourier relation maps tilted wavefronts at the mirrors to displaced positions at the output ports.

In the specific implementation, input port 12, lens 72a, lens pair 75a/75b,

10 lens 72b, and the tiltable mirrors are spaced at approximately equal intervals, with the focal length of the lens defined by lens pair 75a/75b being twice that of lenses 72a and 72b. This is not necessary, but is preferred. With these focal lengths and relative positions, lenses 72a and 72b define a 4f relay between input port 12 and the tiltable mirrors. Furthermore lens pair 75a/75b (treated as one lens), but encountered twice,

15 defines a 4f relay between the input port and the output ports. The optical system is preferably telecentric.

Figs. 7A and 7B are schematic top and side views, respectively, of a wavelength router 70' according to an embodiment of the invention. This embodiment is a folded version of the embodiment of Figs. 6A and 6B, and relates to that embodiment in

20 a similar way to the way that the embodiment of Figs. 1A-1C is a folded version of the embodiment of Figs. 2A and 2B. Like the embodiment of Figs. 1A-1C, wavelength router 70' uses a reflective diffraction grating 25. In view of its folded nature, this embodiment uses single cylindrical lenses 72 and 75 corresponding to lens pairs 72a/72b and 75a/75b in the embodiment of Figs. 6A and 6B.

25 The operation is substantially the same as in the embodiment of Figs. 6A and 6B except for the folding of the optical path. In this embodiment, the light encounters each lens four times, twice between the input port and the tiltable mirrors, and twice on the way from the tiltable mirrors to the output ports. It should be noted that diverging light encountering lens 75 is made less divergent after the first encounter and

30 parallel (collimated) after the second encounter.

generally to the wavelength router shown in Figs. 1A and 1B, except that the spherical focal power is incorporated in the grating itself. Thus optical power and dispersion are combined in a single element 95. This can be accomplished by ruling the grating on a curved surface, or by ruling curved grating lines on a flat surface. One popular

5   alternative to the ruling engine for providing these grating lines is a holographic method in which photoresist is spun onto the grating substrate and exposed with the interference pattern from two diverging beams of light emanating from the intended source and focal points of the grating. The exposure light is at the midband wavelength or at an integer multiple of the midband wavelength. The exposed photoresist may be developed and

10   used as is, or used as a barrier in an etching process.

              Figs. 9A and 9B are schematic top and side views, respectively, of a wavelength router 100 according to an embodiment of the invention. This corresponds generally to the wavelength router shown in Figs. 7A and 7B, which use cylindrical lenses and tilting mirrors, except that the cylindrical focal power is incorporated in the

15   grating ruling in a single element 105. The focal power in the dimension of the top view of Fig. 9A is twice that in the top view of Fig. 9B. The holographic version of this grating may be constructed by exposing photoresist with the interference pattern from one diverging beam and one line source of light emanating from the intended source and focal line of the grating.

20

Band Shape and Resolution Issues

              The physical positions in the plane of the retroreflector array correspond to frequencies with a scale factor determined by the grating dispersion and the lens focal length. The grating equation is $Nm\lambda = \sin\alpha \pm \sin\beta$ where N is the grating groove

25   frequency, m is the diffraction order, λ is the optical wavelength, β is the incident optical angle, and α is the diffraction angle. The lens maps the diffraction angle to position, x, at its back focal length, f, according to the equation $x = f\sin\alpha$. With the mirrors in the back focal plane of the lens, we have a linear relation between position in the mirror plane and the wavelength, $\lambda Nm = x/f \pm \sin\beta$. For a small wavelength a

30   change in frequency is proportional to a change in wavelength. This gives us a scale

Fig. 10A shows a preferred substantially trapezoidal band shape. In short, this is achieved by making the resolution of the grating finer than the size of the mirrors sampling the frequency domain. For an extremely large ratio of the grating spot size to the mirror size, the band pass response for each channel would merely be the rectangular response given by the mirror position in the perfectly resolved frequency plane of the grating. For finite grating resolution, the band pass response is a convolution of the spot determined by the diffraction from the grating with the rectangular sampling of the mirror. The result of such a convolution is depicted in Fig. 10A for a grating with a Gaussian like spot with finer resolution in the mirror plane than the mirror size. It is preferred for embodiments of the invention to provide a large ratio of mirror width to grating resolution because the resultant trapeziodal band shapes have a large usable flat top region as compared to the size of the unusable portion between bands, and this makes the utilization of the spectrum more efficient.

Fig. 10B also shows a differential path length in the optical beam at the angle of diffraction from the grating. This differential path length determines the frequency resolution of the grating. Within an order unity coefficient, determined by the transverse shape of the optical beam, the frequency resolution is the speed of light divided by this differential path length. Specific embodiments have optical bands separated by the ITU spacing of 100 GHz or finer. Consequently, it is preferred that the grating resolution be 10 GHz or finer to allow for a large flat band shape between channels, which will permit low-loss transmission of OC-768 data on 100 GHz channel spacings, or OC-192 data on 25 GHz spacings. This 10 GHz or finer grating resolution requires a differential path length of 3 cm or longer. In the folded geometry of Fig. 1A, this 3 cm is the round trip differential path length, or a one way differential of 1.5 cm.

Fig. 10C shows a router 10''' where the differential path length is in a glass wedge 107. This embodiment corresponds to that of Fig. 1A. It is highly preferred that the center wavelength for these wavelength routers be stable with temperature. The 3-cm differential path length corresponds to approximately 20,000 waves at the preferred center wavelength of 1550 nm. The preferred design has a change in the differential path length of less than one part in 20,000 over the preferred temperature range of at least 50°C. This

the wavelength router containing the differential path length wedge 107 is built in the preferred case of a glass that has thermal coefficient of less than one part in one million.

Attached hereto as an Appendix and filed as part of this application is a presentation, titled "Wavelength Router, also referred to as Wavelength Routing Element™ or WRE," containing 28 pages (slides) on 7 sheets. This presentation includes

5   additional details and features of embodiments of the invention, and further shows how the invention can be incorporated into optical networks. The entire disclosure of the Appendix is incorporated by reference for all purposes.

Conclusion

While the above is a complete description of specific embodiments of the

10   invention, various modifications, alternative constructions, and equivalents may be used. For example, Figs. 11A and 11B show a wavelength router 10'''' which uses a prism 110 instead of a grating as shown in the embodiments described above. The embodiment of Figs. 11A and 11B correspond to the embodiment of Figs. 2A and 2B, and corresponding reference numerals are used.

15   Additionally, while the dynamically configurable routing elements (retroreflectors and the like) were described as including movable elements, switching could also be effected by using electro-optic components. For example, an electro-optic Fabry-Perot reflector could be used.

Therefore, the above description should not be taken as limiting the scope

20   of the invention as defined by the claims.